MEMORANDUM

NGST

Project Office

5 December 1996

A development plan for NGST detectors

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1. Scientific, instrumental and operational requirements

1.1 Wavelength coverage

The prime science program of NGST dictates observations in the near infrared (NIR) band[1], from 1 to 5 microns . However, it is advantageous to extend the coverage to the visible, down to about 0.6 microns, in order to fully characterize spectrally all the objects in the field. In the case of the core program, this would permit the discrimination by photometric redshift of the foreground galaxies in order to exclude them from a high redshift survey. The extension into the visible can be justified technically on the ground that it does not impose many special constraints. This is true as long as the observatory nominal performance remains specified for the near infrared and that degraded performance in the visible is acceptable.

There is also a strong scientific interest in extending the wavelength coverage of NGST to the thermal infrared (TIR), from 5 to at least 10 and possibly 20 microns, where a cooled space telescope exhibits large sensitivity gains over ground telescopes. Figure 1gives the temperature at which the telescope and instruments need to be as a function of the desired wavelength upper limit. Cooling the telescope optics to about 75K in order to assure negligible thermal emission up to about 10 microns should be relatively easy. Going to lower temperatures may be more difficult because it requires better shielding from the sun, better control of thermal leaks and possibly special mechanisms and materials to work at 30 or 40 K. It would also require active cryogenic cooling of the detector.

The required coverage can thus be evaluated as follows:

- 0.6 to 1 micron: highly desirable
- 1 to 5 microns: essential
- 5 to 20 microns: very desirable

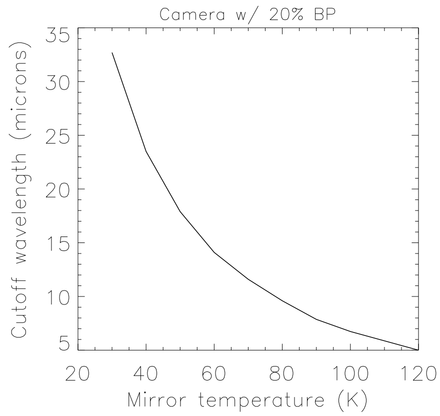


Fig. 1 Cutoff wavelength as a function of the mirror temperature. The cutoff wavelength is defined as that wavelength where the thermal emission at the detector is equal to the zodiacal light. This is calculated for the broadband imaging mode with 20% bandpass.

1.2 Array size

A large field of view is vital since a significant proportion of the NGST science program involves surveys: the larger the field of view, the more efficiently will the prime survey science be carried out[2]. Besides cost, the practical limits are set by the telescope optics and packaging, with the latter being the most stringent. Preliminary engineering studies of the science instrument module have shown that a field of 4x4 arcminutes for the near infrared camera and 3x3 arcminutes for the near infrared spectrograph was achievable, but close to the packaging limit[3]. Because science program thermal infrared observations deal primarily with specific targets as opposed to surveys, a field of 1x1 arcminute is sufficient.

As long as sensitivity is not detector limited, but dominated by the zodiacal light natural foreground or thermal emission of the optics, critical sampling, or even oversampling, will not hurt detectability. In this case it is advantageous to critically sample the image in order to benefit from the full spatial resolution of the telescope.

For faint object spectroscopy, where, even at low spectral resolution, detector background tends to be prevalent, it is on the contrary preferable not to critically sample, but to settle for a spatial resolution of order of the size of the objects of interest. This maximizes sensitivity without much drawback since detailed spectroscopy of faint objects would not be possible anyway. The highest surface brightness component of distant galaxies is of an approximately constant angular size, between 0.1 and 0.3 arcsecond, regardless of their distance, due to a combination of relativistic effects and galaxy formation processes. Thus, for faint object spectroscopy, 0.1 arcsecond is a practical spatial resolution supplying about 2 pixels in the direction perpendicular to the dispersion .

Based on these premises, Table 1 gives the array size required for the camera as a function of wavelength assuming Nyquist sampling. The calculation assumes a telescope aperture of 8 meters. Using the same Nyquist sampling criterion, the array size would be 3/4 of these values (in number of pixels) for a 6 meter telescope. However, if packaging permits, it may be advantageous to keep the array size at the same values as for the 8 meter telescope, thereby increasing the field of view by about 30% and recovering some of the surveying efficiency lost because of the smaller diameter.

Table 1 Camera array size

Central wavelength (microns)	*Field (arcmin)*	*Number of pixels*	
		Nyquist sampled (pixels)	*Proposed (pixels)*
0.8	4 x 4	23,000 x 23,000	8000 x 8000
1.5	4 x 4	12,300 x 12,300	8000 x 8000
2.5	4 x 4	7300 x 7300	8000 x 8000
4	4 x 4	4600 x 4600	8000 x 8000
8	2 x 2	1200 x 1200	1000 x 1000
16	2 x 2	600 x 600	1000 x 1000

While it appears possible that the TIR array be obtained directly as a single chip, the NIR arrays must be mosaiced. Three possible implementations have been proposed which are schematically shown in Figure 2. The required individual focal plane arrays are 2k x 2k or 4k x 4k in size built using individual 1k x 1k (or possibly 1k x 2k) individual arrays. Butting capability is required, but this is facilitated by the fact that gaps between individual chips are not detrimental, since most observations will be for surveys. Gaps totalling less than 10 % of the physical size of the array are acceptable.

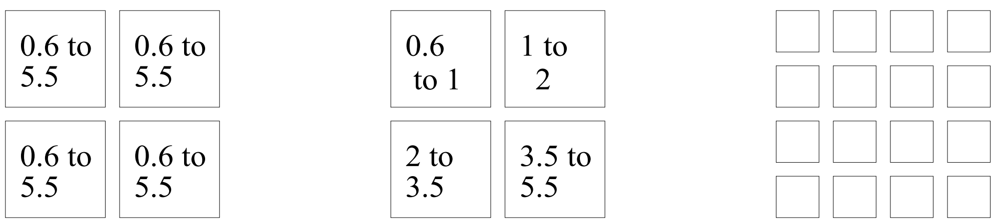


Fig. 2 Three possible implementations for the NIR focal plane arrangement. At left, the 4'x4' field is fed to 4 subcameras of a more manageable 2'x2' field size with mosaiced 4k x 4k focal plane arrays. Each of these subcameras are identical and use the same type of detector covering the entire spectral NIR band (GSFC scheme). Spectral bands are selected in each subcamera by filters. The solution shown at the center follows the same beam splitting principle, but each subcamera is now specialized spectrally, and detectors may be different and optimized for each subspectral band (TRW scheme[4]). In these first two cases the detectors are mosaiced. At right, the field of view is split into multiple beams each feeding a camera and either a single detector chip or a modestly mosaiced array which is optimized for a specific spectral band (LMMS scheme[5]).

For the NIR multiobject spectrograph, a field of 3'x3' with 0.1 arcsecond spatial resolution requires an array of about 4k x 4k which is similar to the subcamera requirement.

1.3 Pixel size

The physical size of the pixels does not affect the science program directly. Only the angle subtended on the sky by each pixel matters and this can be adjusted by changing the telescope and camera optics. However, detector parameters such as dark current, readout noise, cross talk, dynamic range, and sensitivity to cosmic rays can vary with the pixel size. Performance typically improves with smaller pixels but there are practical limits set by cross talk, dynamic range and fabrication techniques.

We also note that smaller pixels are preferable from the point of view of the telescope optics since the magnification of the telescope/camera combination is reduced. For approximate Nyquist sampling (two pixels per Airy disk diameter), the focal ratio at the detector is given by

$$F/D = \frac{2\mathcal{P}}{\lambda},$$

where F is the final system focal length, D the diameter of the primary mirror, $\mathcal{P}$ the pixel size and λ the operating wavelength. At a wavelength of 2 microns, the focal ratio required is equal to the pixel size in microns. The smaller the physical size of the detector, the easier it is to package the fore-optics. In practice, a pixel size on the order of 20 to 30 microns is adequate from this point of view, but the smaller the better.

1.4 Elemental exposure time

For the majority of the science program, observations will be very long, from several hours to days. In practice, observations are split split into shorter exposures to detect and eliminate cosmic rays effects. If Φ is the proton flux, $\mathcal{P}$ the pixel side dimension, and f the allowable fraction of hit pixels, the integration time, t, must be less than

$$t \leq \frac{f}{\Phi \mathcal{P}^2}$$

In the NGST orbit (L2), the cosmic rate is about 1 proton/cm^2-s. For a pixel size of about 20 to 30 microns, and an allowable fraction of hit pixels of a few percents, the elemental exposure time will have to be on the order of 1000 seconds.

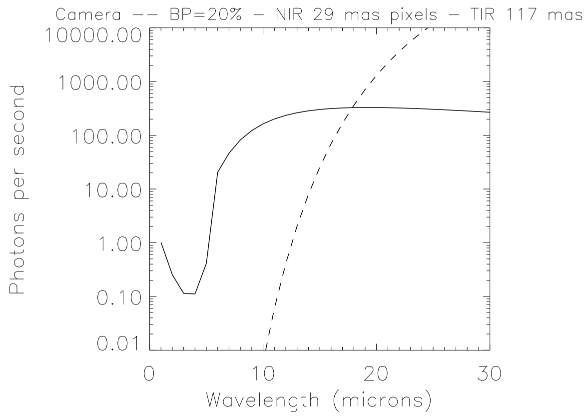
This number is applicable for deep exposures in the near infrared. Exposures of bright objects or deep exposures in the thermal infrared, where the zodiacal foreground is much higher than in the near infrared, the elemental exposure will have to be shorter in practice due to the full well limitation.

1.5 Dark current

The zodiacal light foreground for a nominal 8 meter space telescope is shown in Figure 3 in the two cases of broadband imaging and low resolution spectroscopy. Spectroscopy is the most demanding. If the detector is not to limit sensitivity, the detector intrinsic combined background (i.e. dark current and readout noise averaged over 1000 s) should be less than 0.04 electron per second in the near-infrared (1 to 5 microns) and no more than 4 electrons/s in the thermal infrared (value specified for about 9 microns). In the case of the near infrared detector, budgeting roughly equal sharing between the two contributing sources, i.e. dark current and readout noise, the dark current must be less than 0.02 electron per second. In the case of the thermal infrared detector, the contribution of the readout noise is in practice negligible compared to the dark current, and the dark current needs to be less than 4 electrons/s.

1.6 Readout noise

Currently achieved simple-sampled read noise is on the order of 30 electrons rms. This is large compared to the specified dark current over 1000 seconds of exposure integration (say 0.02 electrons/s i.e. 20 electrons total or 4.5 electrons rms). But one can take advantage of the fact that infrared arrays can be read non-destructively by reading out the array several times during the integration ("up the ramp sampling") or by making multiple readouts at the beginning and end of each frame ("Fowler sampling"). These techniques have been shown to substantially reduce readout noise (Figure 4).



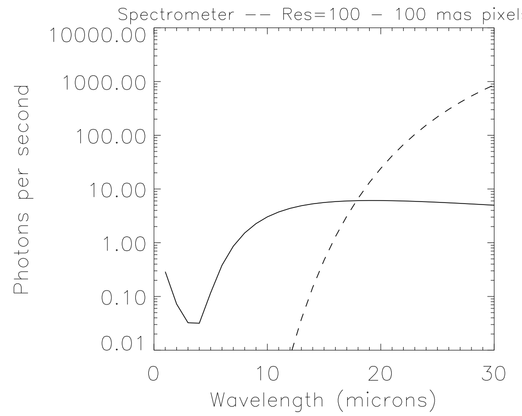


Fig. 3 Zodiacal light foreground (solid line) and thermal optics emission (dashed line) for an 80% filled 8 meter telescope, for broad band imaging (left) and for low resolution spectrography (right). The calculation assumes Nyquist sampling in the middle of the NIR band (about 2.3 microns) and TIR band (9 microns) in the case of imaging, and a spatial resolution of 100 milliarcsecond for spectrography. Nominal throughput and detector efficiency are used for the optics, and the temperature of the main telescope optics is taken as 40K. The recommended maximum combined level of detector dark current and readout noise are shown for each band by the dotted line.

1.7 Quantum efficiency

Clearly, the highest quantum efficiency (QE) is desired, but this should not be at the expense of continuous wavelength coverage. Antireflection coatings may be used on condition that the QE be roughly uniform over the desired wavelength coverage. If minor tuning is possible, the QE should peak where the corresponding gains benefit the overall sensitivity the most. This is near 3.5 microns for the NIR band where the zodiacal light is at its lowest, and between 5 and 12 microns for the TIR band where the zodiacal light and optics thermal emission are low relative to detector noise.

1.8 Full well

Bright objects in the field, such as stars or nearby galaxies, can be left to saturate since the vast majority of NGST's science program are observations of faint objects only. In infrared detectors, saturation is of no consequence: pixels are self-limiting which prevents damage, and there is no bleeding to nearby pixels.

Therefore, the full well requirement only depends upon the scientific program, that is to say on the the minimum desired span from the faintest to the strongest signal in a given field.

In near infrared and background-limited observations, which will be the most frequent, the required dynamic range is not very constraining. Here is a typical example for wide bandpass imaging in the near infrared. The zodiacal light gives 0.1 electron/s per pixel, so that, if detector dark current and readout noise are negligible, and one assumes critical sampling (i.e. with 4 pixels for each resolution element) the faintest object signal for a signal to noise ratio of 10 in a 1000 second exposure will be about 250 electrons total or 60 electrons per pixel. If one desires to cover a range of 7 magnitudes (intensity ratio of 600) for the objects of interest, the brightest object will have a signal of 36,000 electrons. With some margin, a 50,000 e^- full well would be acceptable. Actually this is quite conservative since in most cases images will be built with multiple 1000 second exposures increasing the signal to noise ratio accordingly. Such a dynamic range would also be sufficient in multi-object

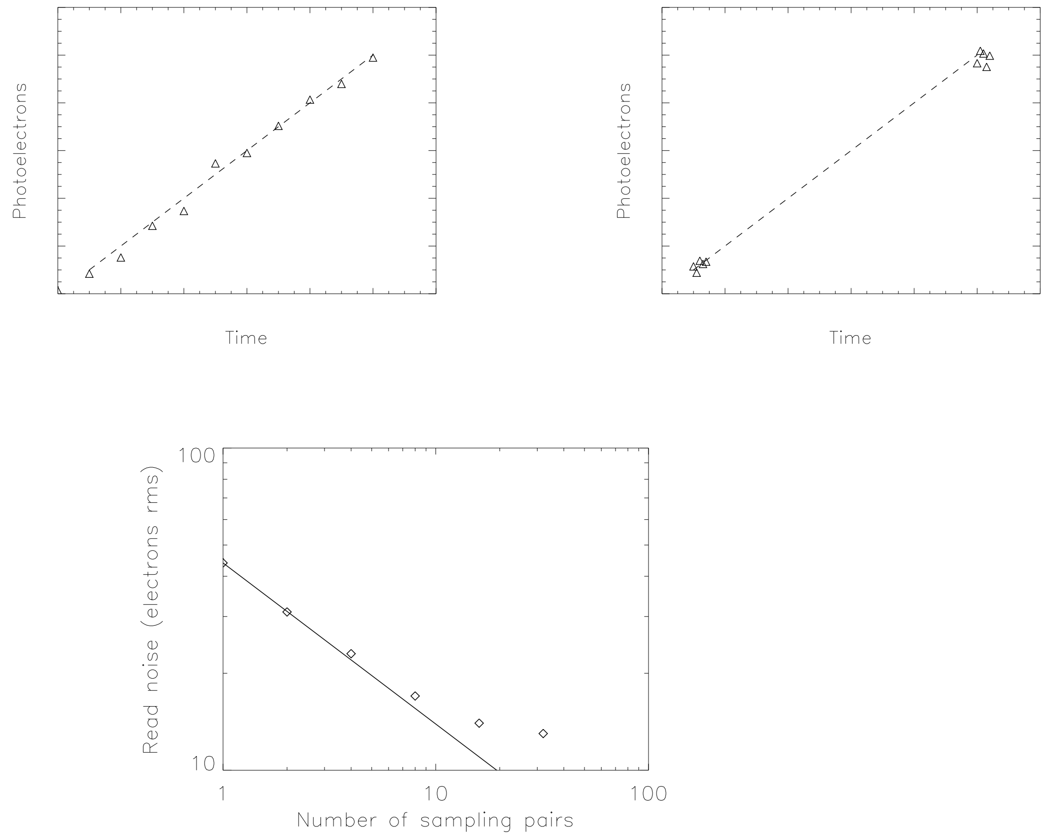


Fig. 4 Up the ramp (top left) and Fowler (top right) multiple sampling reduces readout noise substantially by beating down *random* effects in the addressing noise. Because the defining points at each end of the integration flux line have maximum leverage in the line fitting process, Fowler sampling is better by a factor of $\sqrt(2)$ for white noise over linearly spread sampling. With Fowler sampling, readout noise can be substantially reduced and follows the expected inverse square law up to about 8 samples (bottom). Beyond 8 samples, *systematic* effects become significant and the gain plateaus out (e.g. temperature induced drifts – differences as small as 50 mK in the chip have a measurable effect) By sampling 8 times at the beginning and end of each exposure, the readout noise can be reduced by a factor of about 3. The data shown was obtained with the Aladdin chip with a 60kHz bandwidth[6]

spectroscopy where a 5 magnitude maximum contrast between emission and absorption lines is combined with a 5 magnitude range in the scene, assuming an individual frame signal to noise ratio of 1 for the faintest line in the faintest object, and again critical spatial and spectral sampling.

In the thermal infrared, where the zodiacal light gives about 100 electrons/s, a deeper well may be desirable, but 50 to 100,000 electrons would be acceptable with a nominal exposure time reduced to 100 seconds or so.

1.9 Number of outputs and readout time

No portion of the science program requires very short exposures over a large field. However, readout time is important in as much as it can be a dead time which affects the overall observing efficiency. This is particularly the case if Fowler sampling is used, and less so for up-the-ramp sampling.

For example, with 8 Fowler sampling pairs and a 3 μs readout time per pixel, a four output 1k chip (e.g. four 512 x 512 quadrants) will require $512^2 \times 16 \times 3\,10^{-6} = 12$ seconds to read. With 1000 second elemental exposures, this represents 1.2 % lost in observing efficiency, a small fraction, but not negligible compared to other sources of efficiency loss (optics throughput, pointing dead time, etc.).

Pixel readout speed, the number of outputs and the readout scheme should be designed so as to keep the overall readout dead time to less than 1 or 2 %.

1.10 Detector operating temperature

Low dark current for the near infrared detectors operating up to 5 microns requires temperatures in the 30-40 K range (Figure 5). The science instrument module may be cooled to that temperature through passive cooling. But even if the optics and the science instrument module as a whole are at a higher temperature, it will be possible to passively cool the detector to that range using a dedicated radiator. The thermal infrared detector may require a temperature lower than 30 K which can only be obtained with active cooling or stored cryogens. Although this is considered feasible, it has a significant impact on the observatory design and cost and should be avoided if alternate detector selections are acceptable.

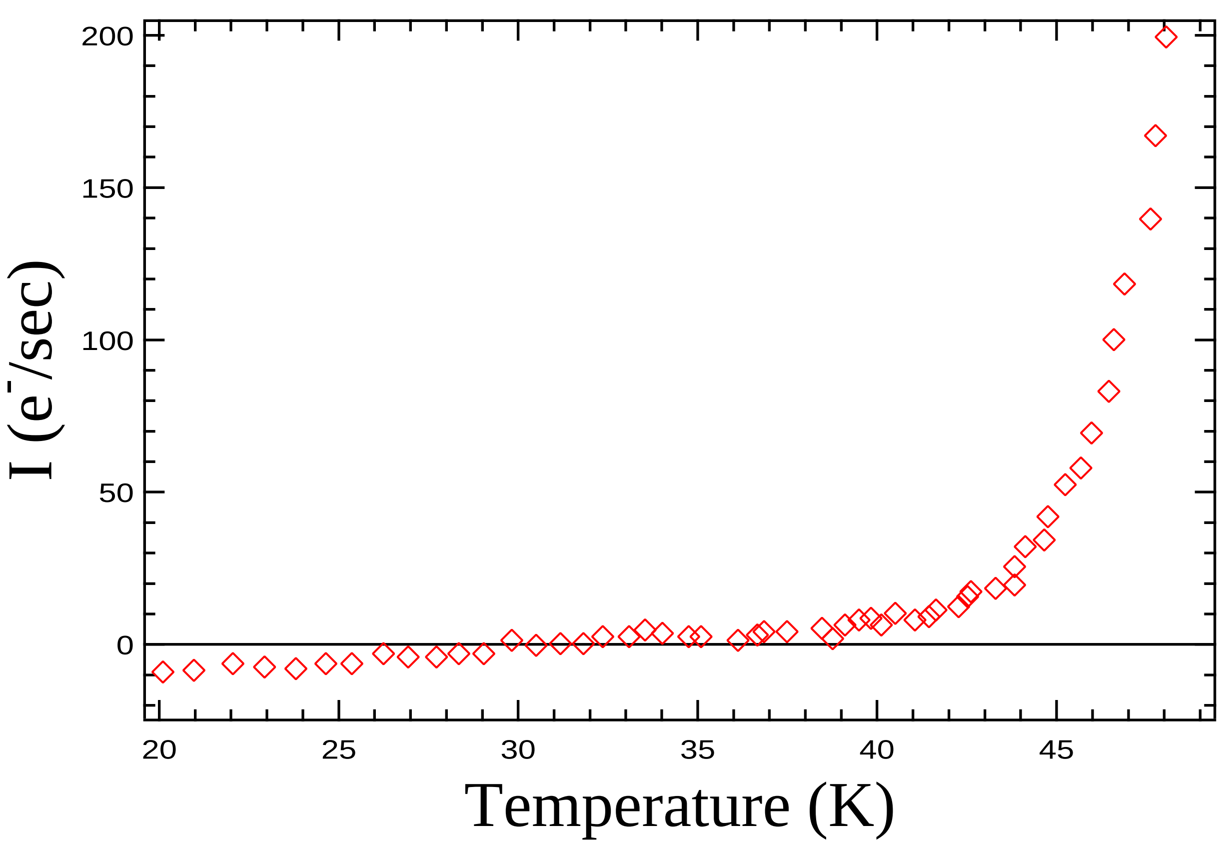
Fig. 5 Typical effect of temperature on dark current (InSb detector).

1.11 Heat dissipation

NGST's science instrument module is to operate at 35 K, and be cooled by passive means. At this temperature, the cooling power of a radiator facing deep space is only 80 milliWatts per square meter. With the radiator for the science instrument physically limited to a few square meters, it is essential that the *average* heat dissipation of the arrays be kept low, on the order of 2 mW per 1k x 1k array module over a duty cycle.

1.12 Summary of required performance

The resulting required detector performance is summarized in Table 2.



200
150
100
50
0
I (e$^-$/sec)
20
25
30
35
40
45
Temperature (K)

Table 2 Desired detector array characteristics

Parameter	*NIR*	*TIR*
Wavelength range (microns)	0.6 to 5	5 to 20
Total number of pixels	8k x 8k	1k x 1k
Possible focal plane array size (mosaiced)	4k x 4k	1k x 1k
Possible individual array size	1k x 1k	1k x 1k
Dark current (e^-/s)	$\leq$0.02	$\leq$5
Single sampling readout noise (e^-)	$\leq$15	$\leq$30
Average quantum efficiency (%)	> 80	> 50
Full well (e^-)	> 50,000	> 50,000
Read out dead time (s)	$\leq$ 12	$\leq$ 12

2. Current performance of near-infrared and thermal infrared arrays

The main detector materials for the desired infrared wavelength coverage are shown in Figure 6. Among these, the best performers and most mature are InSb and HgCdTe for the 1-5 micron region, and Si:As IBC for the 6 to 20 micron region. The other materials have been tried but have lower performance or face implementation problems.

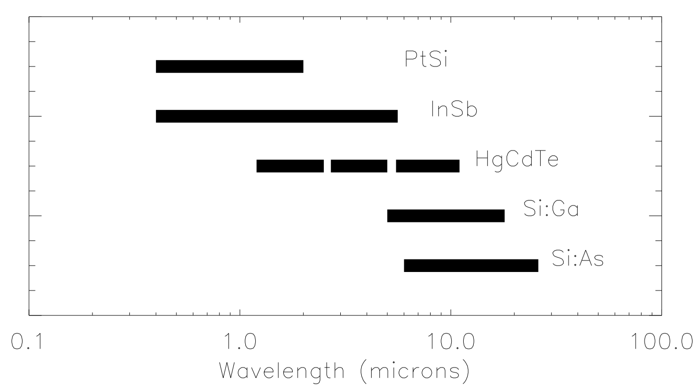


Fig. 6 Most promissing IR detector materials.

The current state of the art for these three types of detector is shown in Table 3.

Table 3 State of the art detector performance

Item	*InSb*	*HgCdTe*	*Si:As IBC*†
Representative array	"ALADDIN"	"HAWAII"	SIRTF
Manufacturer	SBRC	Rockwell	SBRC and Rockwell
Wavelength range (microns)	0.6 - 5.5	1 - 2.5*	5-28
Format	1024 x 1024	1024 x 1024	256 x 256
Single sample read noise (e^-)	50	34	50
Dark current (e^-/s)	< 0.1	< 0.1	< 10
Well depth (10^5 e^-)	3	0.9	1
Pixel size (microns)	27	18.5	30
Operating temperature (K)	35	80	6K
Quantum efficiency	85% (average 0.9-5μ)	66% (K-band)	40% (average 5-25)
Readout time (μs/pixel)	3	3	3
Power dissipation (mW)	<3	<3	<1

* HgCdTe detectors can be designed to cover longer wavelengths. 1 to 5 micron HgCdTe detectors have characteristics similar to those of the InSb (dark current controlled by the bandgap, which is only a function of the cutoff wavelength). Longer wavelength HgCdTe need to be operated at lower temperatures, similar to that of InSb (35K).

† IBC= Impurity Band Conduction.

3. Development plan

3.1 Detector selection and improvement program

Comparing the desired requirements to current performance shows that arrays presently available are approaching NGST goals. However, dark current and readout noise would need to be reduced by a factor of about 5. Higher quantum efficiency in the case of the silicon based detector would be desirable, and might be obtained with appropriate antireflection coating.

In the case of InSb arrays, "EDKIT" a DoD research and development program is already in place at SBRC for lowering dark current at higher temperature, and a readout noise reduction program has been proposed for funding by NASA in FY 97 (NRA 96-OSS-07). There may be some value in funding a similar program for HgCdTe detectors to ensure multiple sources of supply, and backup technologies, are available. However, in view of the better performance and maturity of InSb detectors overall (higher QE, wavelength coverage extended into the visible), and the fact that a development program is already funded, we recommend to wait for the end of this program, in about 18 months, to evaluate the need for a competitive development program using 5 micron cutoff HgCdTe detectors. A very modest effort ($25K) aimed at assessing the applicability of the results of this EDKIT InSb program to NGST would, however, be valuable, in addition to the proposed effort on low-noise InSb.

For the thermal IR detector, the Si:As IBC detector would be an obvious choice if the required operating temperature were not difficult to achieve. Although the scientific case for an extended thermal infrared coverage and the practicality of 6-8 K operating temperature are not fully established yet, we also recommend initiating a focussed development program for the Si:As IBC type of detector.

We also recommend that alternate detector solutions be explored, in particular with materials which may not extend as far in wavelength as Si:As IBC and may not have as low a dark current, but which could still be acceptable while being operated at higher temperature. Two such possibilities are the use of HgCdTe tuned for the 5 to 12 micron range, or a quantum well infrared photoconductor (QWIP). We also recommend that a modest program be conducted in parallel to assess the feasibility of producing Si:Ga IBC detectors (18 micron cutoff and about 8-10K operating temperature).

In summary we are recommending to pursue agressively the InSb option for the NIR detector and Si:As IBC for the TIR, once the current technological developments are complete, and to explore all available options, even those with degraded performance (long-wave HgCdTe, Si:Ga IBC and QWIP).

The selection of the most promising NIR and TIR detectors will be made at the end of the first full detector iteration. This will allow resources and effort to be concentrated on a single detector type for the following iterations.

3.2 Laboratory testing

Laboratory testing of infrared focal plane arrays at the level required for NGST is extremely delicate. This is especially true in the case of dark current measurements (0.01 e^-/s level), where spurious sources and internal thermal emissions must be avoided. Detector manufacturers are not equipped to make these measurements. Currently, only a handful of laboratories have the technical knowledge and proper equipment to perform the detector evaluation for astronomical applications (NASA/Goddard, NASA/Ames, JPL, NOAO, University of Rochester, University of Arizona, Cornell University, and maybe a few other universities). Some of the existing test equipment can be used but would need to be upgraded to guarantee the accuracy needed for NGST level.

We recommend that the NGST Project Office enter into an agreement with one or possibly two of these organizations to guide the development effort and perform the required evaluation program over the next few years.

3.3 Mosaicing

Producing the focal plane arrays for the large field desired necessitates mosaicing. This has been performed successfully in the past with various kinds of detectors on a smaller scale, but not to the extent that is required for some of the concepts proposed (e.g. a mosaic of sixteen 1k x 1k in the GSFC scheme). Some curvature may also be required to match the focal surface if one is to avoid field flatteners.

It will thus be important to demonstrate the overall mosaicing technique, develop wiring and mounting systems to minimize gaps, and then submit prototypes to careful radiometric testing, thermal cycling and space qualification.

3.4 Focal plane array prototyping

Although the development of focal plane arrays for NGST does not require major technological breakthroughs, extending manufacturing processes and assembly techniques to reach the desired goals is not trivial. After consultation with potential manufacturers, we estimate that this will require at least two iterations for development purposes and a third one for producing a flight prototype. A prototype iteration, which typically includes revised readout multiplexers and detector layers is a long process which requires 7 to 9 months. It must thus be realized that even the modest improvement of the current state of the art that NGST requires will take several years.

3.5 Evaluation by astronomers

"Open-loop" engineering, no matter how excellent, and laboratory testing can only go so far. To guarantee the full applicability of detectors to astronomical observations, users should be involved in the device development stage and the resulting detectors must be submitted to sky tests and actual usage by practicing astronomers. As this has been done very successfully in the case of other space astronomy detectors, we recommend an extensive testing program using ground telescopes for the NIR detectors and a more modest one for the TIR detector (because of the backgound limitations on the ground in the TIR band). This will assist in determining the exact performance of the detectors, establishing the impact of possible defects or features which fail to meet specs, and, in general, in evaluating the scientific usefullness of these detectors. More importantly, actual usage will be key in designing control electronics and operational procedures which maximize observational usefulness.

3.6 Development flowcharts

Based on the above remarks, our proposed development plan is shown in Figure 7.

3.7 Budget

The approximate budget required for the technological development described above is shown in Table 4.

3.8 Overall schedule

The overall schedule for the development and integration of the detectors is briefly summarized in Table 5.

Table 5 Development schedule

Item	*Period*
Performance improvement (NIR)	Oct 1996 to Mar 1998
Selection and performance improvement (TIR)	Oct 1996 to Mar 1998
Two test iterations	Mar 1998 to Oct 1999
Evaluation by astronomers	Oct 1999 to Oct 2000
Flight prototype and test	Oct 2000 to June 2002
Evaluation by astronomers	June 2002 to June 2003
Flight unit	June 2003 to June 2004
Integration in instrument	June 2004 to June 2006

4. References

1. *Exploration and the search for Origins: a vision for ultraviolet-optical-infrared space astronomy*. Report of the "HST and Beyond" Committee, AURA, 1996.

2. *A strawman science program for NGST*, Memo by M. Stiavelli, S. Cascertano, R. Burg and P. Bely, October 1996.

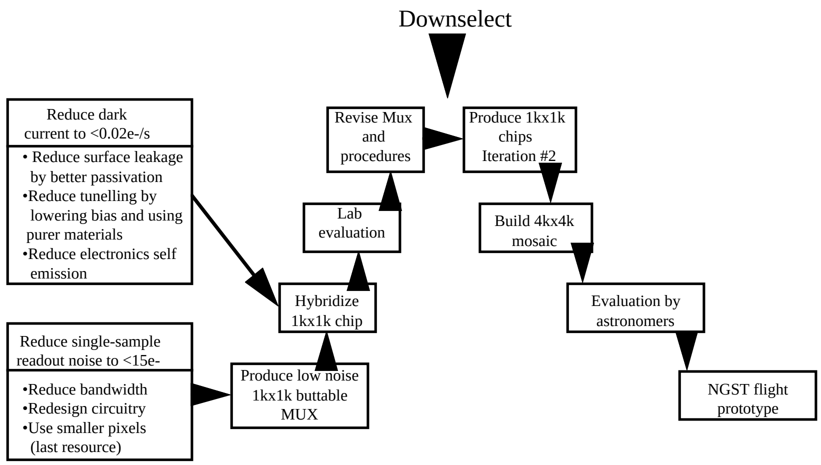
3. *Science Instrument Module for NGST*, an interim report by the Integrated Product Team for the GSFC NGST study, August 1996.

4. *TRW-led NGST feasibility assessment study results*, August 1996.

5. *LMMS-led NGST final study report*, LMMS/PO86946, August 1996.

5. A. Fowler et al, SPIE 2816, 1996

Fig. 7 Proposed development plan for the NIR detector (top) and the TIR detector (bottom).


Downselect
Reduce dark current to <0.02e-/s
• Reduce surface leakage by better passivation
•Reduce tunelling by lowering bias and using purer materials
•Reduce electronics self emission
Reduce single-sample readout noise to <15e-
•Reduce bandwidth
•Redesign circuitry
•Use smaller pixels (last resource)
Produce low noise 1kx1k buttable MUX
Hybridize 1kx1k chip
Lab evaluation
Revise Mux and procedures
Produce 1kx1k chips Iteration #2
Build 4kx4k mosaic
Evaluation by astronomers
NGST flight prototype

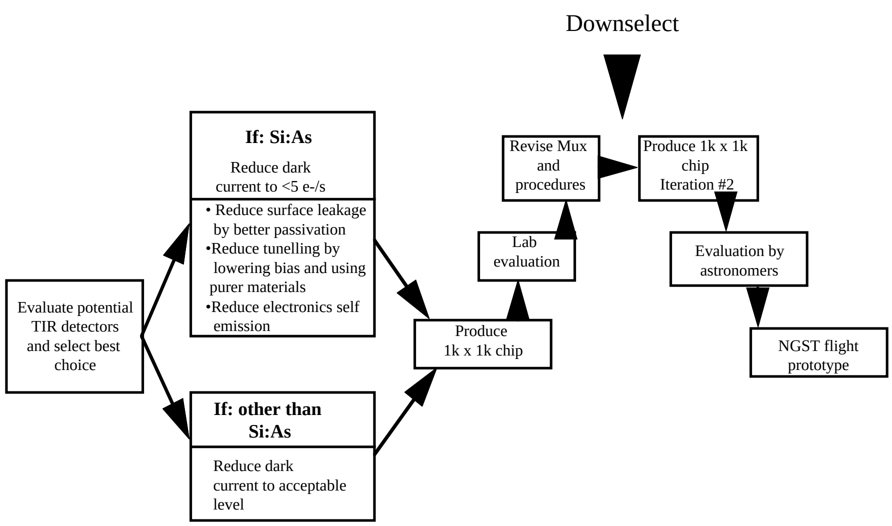

Downselect
Evaluate potential TIR detectors and select best choice
If: Si:As
Reduce dark current to <5 e-/s
• Reduce surface leakage by better passivation
•Reduce tunelling by lowering bias and using purer materials
•Reduce electronics self emission
If: other than Si:As
Reduce dark current to acceptable level
Produce 1k x 1k chip
Lab evaluation
Revise Mux and procedures
Produce 1k x 1k chip Iteration #2
Evaluation by astronomers
NGST flight prototype

Table 4 Detector development cost estimate (1996 K$)

Fiscal year	1997	1998	1999	2000	2001	2002
NEAR INFRARED DETECTOR						
Research and Development	–					
Dark current and readout noise reduction						
Iteration 1 (multiple approaches)						
Conceptual design	150					
Readout	300	300				
Detector	285	285				
Hybridization	125	125				
Test equipment upgrade	150	150				
Lab testing			300			
Iteration 2						
Readout			300			
Detector			190			
Hybridization			130			
Mosaicking				100		
Lab testing					100	
Ground based camera				500*	500*	
Astronomical evaluation						100
Flight prototype						
4k x 4 k focal plane array						1000
THERMAL INFRARED DETECTOR						
Research and Development						
Dark current and readout noise reduction	200					
Iteration 1 (multiple approaches)						
Conceptual design	50					
Readout	300	300				
Detector	285	285				
Hybridization	125	125				
Test equipment upgrade	150	150				
Lab testing			300			
Iteration 2						
Readout			300			
Detector			190			
Hybridization			130			
Mosaicking				100		
Lab testing					100	
Ground based camera				500*	500*	
Astronomical evaluation						100
Flight prototype						
1k x 1 k focal plane array						1000
Yearly total	2120	1720	1840	1200	1200	2200
Grand total						**10,280**

* The NASA contribution assumed here represents 30% of the cost of an infrared camera for a ground based large telescope (e.g. Gemini). This includes the design and fabrication of the control electronics.